Prospects for the first $W$ mass measurement @ LHC

Luca Perrozzi (ETH Zurich)
On behalf of the CMS and ATLAS Collaborations
Motivations

• A precise measurement of $M_W$ provides a crucial test of the SM
• The EWK gauge sector of the SM is mainly constrained by three parameters
  – $\alpha_{EM}(M_Z)$, $G_F$, $M_Z = 91.1876 (21)$ GeV
• Related to $M_W$ at tree-level, via $M_W^2 = \pi \alpha_{EM} / \sqrt{2} G_F \sin^2 \theta_W$ where $\cos \theta_W = M_W / M_Z$
  – Top and W boson mass (over)constrain the mass of the Higgs boson, and possibly new particles beyond the standard model
    • SUSY particles can contribute $O(100)$ MeV to $M_W$ via loop corrections
    • Progress on $\Delta M_W$ has the biggest impact on the SM fit (need to target < 10 MeV uncertainty)

Measurement strategy

- **W** production is abundant at hadron colliders
  - $O(100M)$ leptonic **W** events in LHC Run 1 (stat uncertainty << 5 MeV)
- Measurement requires control of several aspects
  - Theoretical: PDF, QCD (boson $p_T$, polarization), QED (FSR)
  - Experimental: lepton momentum scale, hadronic recoil resolution
- Template analysis: compare DATA/MC for transverse observables
  - Muon $p_T$ → most affected by $p_T(W)$ uncertainties
  - Missing $E_T$ → most affected by detector resolution effects
  - $m_T$ → best compromise between TH and EXP (cfr de Rujula et al, arXiv:1106.0396)
- At low boson $p_T$: $m_T \sim 2p_T^{\mu} + p_T^{W}$
- To get 10 MeV on $m_W$: $10^{-4}$ precision on $p_T^{\mu}$ (~40 GeV) and $10^{-3}$ on $p_T^{W}$ (~5 GeV)
Previous measurements: Tevatron

- W mass uncertainties can be factorized into 2 distinct parts
  - Experimental systematics (decrease with statistics)
  - Theory systematics (do not decrease with statistics)

<table>
<thead>
<tr>
<th>Source</th>
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CDF

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CDF, PRD 89 (2014) 072003, arXiv:1203.0275v1 [hep-ex], 2.2 fb⁻¹
D0, PRD 89 (2014) 012005 , arXiv:1310.8628v2 [hep-ex], 4.3 fb⁻¹
Towards the W mass @ LHC

- Measurement sitting on the shoulder of the (Tevatron) giants

- **Statistical precision 7 TeV data (~4.5 fb⁻¹): < 10 MeV / channel**
  - Extrapolating: 8 TeV data (~20 fb-1): < 5 MeV / channel
  - Each experiment can reach << 5 MeV statistical precision with Run 1

- **Challenges at the LHC:**
  - Higher pile-up environment → affect hadronic recoil resolution and calibration
  - Different energy regime 2 TeV vs 7/8/13 TeV, p-p instead of p-p collisions, potentially larger theoretical uncertainties
  - $W^+$ and $W^-$ production is not symmetric → Charge-dependent analysis

- **Advantages:**
  - Large calibration samples: 1-2M (@7 TeV) of $Z \rightarrow \mu\mu/ee$
  - Large pseudorapidity coverage
  - MC template built with detector full simulation with latest and greatest overall calibration conditions and detector description
The experimental challenges

More data = higher precision
Interlude: the W-like (Z) mass @ CMS

- **Z mass measurement in “W like” Z → μμ events**
  - central “tag muon” |η|<0.9, other muon removed, MET and \(m_T\) recomputed
  - low background
  - use dilepton system to constrain the theory part

- **Proof of principle intermediate step**
  - Validate tools and techniques to be used in W mass measurement
  - Lead to the improvements in the modeling of W production
  - Statistical uncertainty ~Tevatron level

- **Split the sample: half for calibration, half for the measurement**

- **Caveat: additional systematics need to be accounted for the W mass measurements**
  - PDFs in W production
  - Z → W extrapolation
  - Background

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### CMS PAS SMP-14-007

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Lepton momentum calibration

- Bottom line: use resonances ($J/\psi$, $Y$, $Z$)
  - For low boson $p_T$ $W$: $m_T \sim 2p_\mu^T + p_T^W$
    - To get 10 MeV on $m_W$: $10^{-4}$ precision required on $p_\mu^T$ scale ($\sim 40$ GeV)
    - Resolution less crucial

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Lepton momentum calibration in CMS

- Calibrate muon curvature \((1/p_T)\) using \(J/\psi, Y\) at 7 TeV
- Use a **physically motivated calibration model** to cover the whole \(p_T\) spectrum

\[
k^c = (A - 1)k + qM + \frac{k}{1 + k \epsilon \sin \theta}
\]

- Scale corrections are derived for both Data and simulation
  - Resolution corrections included, accounting for multiple scattering and single hit resolution

Main uncertainties:
- High mass \((J/\psi, Y\) to \(Z\)) extrapolation
- Statistical power of the calibration sample
Recoil reconstruction

- **Hadronic activity balancing boson** $p_T + UE, MPI, pileup

- **ATLAS**: dedicated recoil algorithm for $W, Z$ measurements
  - Sum over calorimeter cells excluding the cells associated to the lepton.

- **CMS**: Particle flow algorithm (pfMET)
  - reconstruction and identification of each particle with an optimized combination of all subdetector information

- Similar resolution between ATLAS and CMS

- **CMS improvement**: tkMET
  - vectorial sum of the pf charged hadron with $dz<0.1$ cm
    - 80% efficiency for charged tracks $p_T>300$ MeV, $|\eta|<2.4$
  - Suppress in-time pileup at reconstruction level not considering pf hadrons/clusters associated to vertices other than the Primary Vertex
  - Also for high pileup 8 TeV sample

- Better sensitivity (resolution) wrt pfMET in $W$(-like) events
Recoil calibration

- Different effects: pileup, UE, soft/hard radiations
  - effective calibration based on Z events
- Useful projections: $u_\perp$, $u_\parallel$: projections of $u$ on axis perpendicular/parallel to boson $p_T$
- Use to compare recoil resolution and response in data and MC

- CMS calibration example in the W-like measurement
  - 2D model with sum of 3 Gaussians vs boson $p_T$
  - Derive corrections, apply them to simulation
  - Correction derived in boson rapidity bins to account for data/simulation discrepancies

- Main uncertainties:
  - Limited statistics of the calibration samples
  - Calibration model (alternative based on adaptive kernel)
W-like (Z) mass analysis results

- Experimental uncertainty ~20 MeV (muon channel)
  - Competitive to Tevatron
  - Electron uncertainty uncorrelated, large gain in sensitivity and valuable cross-check
- “Theoretical” uncertainty ~30 MeV
  - Don’t translate directly to W mass, also Z→W extrapolation (eg recoil calibration) not accounted for
- PDF likely to be larger for W (for Z constrained by \( p_T \) and rapidity meas.)
- QED systematics: on/off NLO EW correction in Powheg-EW (very conservative)
The theoretical challenges

Where are the uncertainties lying?
PDF effects

- PDF uncertainties on $m_w$ dominated by the valence/sea ratio and 2nd generation uncertainties
  - Transverse momentum distribution uncertainties due to uncertainties in the $p_T^W$
    - Contributions from distribution heavy quark PDFs (+non-perturbative parameters)
- Valence/sea PDF uncertainties
  - Determine the rapidity distribution $\rightarrow$ acceptance effects
  - Valence PDFs polarize the W decay along z-direction
- At generator level $\sim 10$ MeV PDF systematics, but differences between sets 20-30 MeV

Figure 4: Summary of the PDF uncertainty on $m_w$ computed with different PDF sets, colliders and final states. The basic acceptance criteria have been used in the left plot, while in the right plot an additional cut $p_T^W < 15$ GeV has been applied.

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Constraining PDFs

• **W charge asymmetry**
  - vs rapidity: \[ A(y) \approx \frac{u_v - d_v}{u_v + d_v + 2 r_s c} \]
    where \( r \approx s/d \) and assuming \( u \approx d \) and \( s \approx s \)
  - most significant improvement in dv

• **W and Z cross sections**
  - Measured enhancement of Z production at central rapidity is interpreted as enhanced strange density
  - Increasing \( s(x) \) (to \( r \approx 1 \)) explains Z data, W unchanged

• **W+charm cross section**
\(p_T^W\) modeling: learning from \(p_T^Z\)

- \(p_T^Z\) measurement
  - Measure \(p_T^Z\), tune parton shower (or resummation parameters) then apply to \(p_T^W\)
  - Constraints from ATLAS measurement: \(\Delta m_W < 5\) MeV assuming no extrapolation uncertainty
  - Caution needed at the LHC: \(Z, W^+\) and \(W^-\) have different from 2\(^{nd}\) and 3\(^{rd}\) generation PDFs (4-8 times larger than Tevatron)

- Modeling of \(p_T^Z/p_T^W\) with state of the art generators → interplay with theory community

- Alternative way: direct measurement of \(p_T^W\)
  - May need dedicated runs at low pileup ≈250 pb\(^{-1}\) at \(\mu=1\), driven by \(Z\) statistics (calibration)
  - 2.5% -5% precision reached on \(p_T^W/p_T^Z\) (three lowest bins) with the 18.4/pb

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arXiv:1606.05864 submitted to JHEP
More QCD: angular distributions

- The measurements of the correlation of the angular distributions with the lepton transverse momentum distributions, are an important ingredient in $M_w$ measurement
  - Measured by ATLAS and CMS on Z events
  - CMS: Comparison of the angular coefficient in the Collin-Soper frame in bins of boson $p_T$ and $|Y|<1$ and $|Y|>1$
  - ATLAS: in bins of $p_T$ and 3 rapidity bins
  - Uncertainty dominated by the PDFs

- Probe QCD corrections beyond the formal accuracy of the calculations.
- Significant deviation from the $O(\alpha_s^2)$ predictions from DYNNLO is observed for A0 – A2 (ATLAS), indicating that higher-order QCD corrections are required to describe the data

[Images and graphs showing data comparisons and theoretical predictions]

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EWK corrections

- Monte Carlo tools usually encode only NLO QCD corrections
- Non-negligible contribution from NLO EWK and cross terms

- FSR modeling also studied (and understood) in great detail

![Graphs showing distributions of $p_T$ for $W \rightarrow \mu \nu$ and $W \rightarrow e\nu$ events.](image)
Summary

- Long standing effort to measure $m_W$ at the LHC
- Status of experimental systematics seems promising and already comparable to the latest Tevatron results
  - Larger statistics will help in pinning them down further
- Precise assessment of theoretical systematic uncertainties being discussed with the theory community
  - No single tool able to incorporate all the latest and greatest QCD and EWK corrections
  - Non trivial $p_T^Z/p_T^W$ prediction
  - Non trivial interplay between PDF, QCD corrections and parton shower
- New analysis and fitting strategies could help in reducing the impact of syst uncertainties
  - Profiling techniques used in Higgs, featuring in situ constraints with ancillary measurements

Current status

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<tr>
<td>Tevatron</td>
<td>$\sim$</td>
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<tr>
<td>LHC</td>
<td>$&gt;$</td>
<td>$&gt;$</td>
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W mass analysis in a nutshell

W mass analysis at a conference
Backup
Further readings and references

Series of workshops to bring together experimentalists and theorists

- November 2014 in Florence: [https://indico.cern.ch/event/340393/](https://indico.cern.ch/event/340393/)
- February 2015 at CERN: [https://indico.cern.ch/event/367442/](https://indico.cern.ch/event/367442/)
- June 2016 at CERN: [https://indico.cern.ch/event/367442/](https://indico.cern.ch/event/367442/)
- Next meeting: November 2016 in Mainz
W-like ingredients

- ½ Z dimuons
- Drop one leg
- Z dimuons
- ½ Z dimuons
- Recoil calibration
- Upsilon dimuons
- Muon calibration
- J/psi dimuons
- Some theory
- W-like measurement

Some theory

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PDF and W,Z production

- Main production at LHC: \( ud \rightarrow W^+ \), \( du \rightarrow W^- \); \( cs \rightarrow W \sim 25\\% \)
  - Quark “x” from \( 10^{-3} \) to \( 10^{-1} \)

- Similar PDFs for W and Z, BUT:
  - charm quark significant to W production (\( \sim (V_{cs}+V_{cd}+c.c.) \), smaller for Z (\( \sim cc \))
  - b-quark contributes to Z production (\( \sim bb \)), negligible to W production (\( \sim (V_{cb}+c.c.) \))

- Strange and charm production \( \sim \) several times larger than in pp in Tevatron
  - Preliminary: 7-9 MeV uncertainty (including experimental effects)
Properties of the W-like system
The strategy of fitting the $Z$ $p_T$ and predicting the $W$ $p_T$ can be applied to any model.

However, different models predict very different $W/Z$ $p_T$ ratios, in particular Pythia8 and Powheg+Pythia8 parton shower models predict a monotonic falling ratio, while predictions based on resummation shows a peak at 5 (3) GeV for $W^-$ ($W^+$).

Plots without cuts on the lepton kinematic.

→ Fits to the same $Z$ $p_T$ data of different models can provide very different predictions of the $W$ $p_T$ distribution.
**W/Z ratio** $q_T$ **spectrum:** perturbative scale uncertainty

In collaboration with L. Talon.

DY$qT$ resummed predictions for the ratio of $W/Z$ normalized $q_T$ spectra. **Uncorrelated** perturbative scale variation band.

DY$qT$ resummed predictions for the ratio of $W/Z$ normalized $q_T$ spectra. **Correlated** perturbative scale variation band.
W Analysis phase space (large $\eta$ lepton and low $p_T W$) important to limit the PDF uncertainty on $W$ mass (Vicini et al. arXiv:1501.05587)

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<td>$W^-$</td>
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Events in the various $w$-like variables statistically correlated

Table 1: Correlation between the $W$-like fitting variables.

<table>
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<td>2. Transverse mass ($m_T$)</td>
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<td>0.70</td>
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We have 50% of common events between the $W$-like Pos dataset and $W$-like Neg dataset.
Towards the W mass @ LHC

• Indicative selection:
  – ATLAS: lepton $p_T > 30$ GeV, MET > 30 GeV, $m_T > 60$ GeV, $u < 30$ GeV
  – CMS: $30 < \text{lepton } p_T < 55$ GeV, $30 < \text{MET} < 55$ GeV, $60 < m_T < 100$ GeV, $u < 15$ GeV